THE ASTROPHYSICAL JOURNAL, 222:585–594, 1978 June 1

LIGHT-ELEMENT ABUNDANCES IN THE WEAK G-BAND STAR HR 6766

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Received 1977 October 3; accepted 1977 December 14

ABSTRACT

A high-resolution spectroscopic study of the weak G-band star HR 6766 has been carried out. Atomic line equivalent widths and broad-band photometric colors have been used to derive $T_{\rm eff} = 4750 \pm 100$ K, $\log g = 2.0 \pm 0.4$, and $v_t = 2.0 \pm 1.0$ km s^{-1}. All iron-peak elements have approximately the same abundance, [M/H] $= -0.15 \pm 0.25$. A spectrum synthesis analysis of the CH G band yields [C/H] $= -1.49$, an underabundance by a factor of 10 relative to a typical giant of similar luminosity. From individual lines of the CN red system and the CN violet band heads, an abundance [N/H] $= +0.23$ is obtained. Oxygen is nearly normal; the forbidden lines are used to derive [O/H] $= -0.38$. The CN red system lines have been used to obtain ^{12}C/^{13}C $= 4.1 \pm 1.5$ and ^{14}N/^{15}N > 10. Finally, log Li $= +0.75$ is derived, and no solid evidence for the presence of ^{6}Li is found.

HR 6766 is compared with other weak G-band stars, and it is found that all may have the common characteristics of low ^{12}C/^{13}C ratios and strong lithium features. The abundances of the CNO group of elements in HR 6766 are consistent with a heavy exposure to the CNO cycle in its interior, followed by mixing of the burning products to its surface. Various scenarios for accomplishing this in a low-luminosity giant star ($\log L/L_\odot = 1.9$) are discussed.

Subject headings: stars: abundances — stars: individual — stars: weak-line

I. INTRODUCTION

Much progress has recently been made in attempts to understand the spectra and interior evolutions of cool giant stars. Increasingly, spectroscopic investigators have turned their attention to the light elements carbon, nitrogen, oxygen, and lithium. The surface abundances of these elements more than any others are indicative of the type of evolution which a star has undergone since it left the main sequence. Some observers have attempted to derive light-element abundances for a large, representative sample of "normal" giant stars (e.g., Lambert and Ries 1977) to test the predictions of normal stellar evolution theory. Others have opted to concentrate on analyses of more peculiar stars (e.g., the work on the barium star ζ Capricorni by Tech 1971) in order to provide theoreticians with more solid data on the extreme conditions to which stellar evolution may proceed. The present work falls into the latter category by presenting an analysis of a star which has extremely little carbon in its envelope.

HR 6766 is the brightest member of a class of stars commonly called weak G-band stars. This designation arises from the fact that, on low- to moderate-resolution spectrograms of these otherwise apparently normal late G and early K giant stars, the G band of CH is either absent or extremely weak. Stellar evolution calculations for stars with initial compositions somewhat like the Sun show that those stars should deplete their envelope carbon contents by factors of 2 or 3 (see, for example, Dearborn, Eggleton, and Schramm 1976). Since the G band of CH is saturated in K-type stars, such carbon depletions could hardly make the G band disappear. It is therefore obvious that the weak G-band stars represent a class of objects which either were formed from carbon-poor interstellar matter or have undergone a rather peculiar form of stellar evolution.

Several properties of the class of weak G-band stars have been described in the early work of Bidelman (1951). Greenstein and Keenan (1958) discussed approximate carbon and nitrogen abundances for a number of giants of varying CH strength, including a couple (HR 885 and HR 6791) with very weak G bands. Bidelman and MacConnell (1973) have identified a number of weak G-band stars in the southern hemisphere, using the Michigan Curtis-Schmidt telescope at Cerro Tololo Inter-American Observatory. Recently, Dean, Lee, and O'Brien (1977, hereafter DLO) have published colors and spectral classifications for 24 of the stars on the list of Bidelman and MacConnell (1973). Also, Hartoog, Persson, and Aaronson (1977, hereafter HPA) have used intermediate-band CO indices to show that all weak G-band stars exhibit extremely weak CO absorption when compared with normal giants of similar spectral type. Norris and Zinn (1977) have discussed the weak G-band effect in globular cluster stars.

Certain characteristics of the spectrum of HR 6766 have been previously noted. Using 9 and 18 Å mm^{-1} spectrograms, DLO point out the existence of a rather strong lithium feature in HR 6766 and derive a ratio [Li/Ca] $\approx +1.5$. Their spectra also indicate that the CH G band is absent in HR 6766 and that the violet CN bands at 4215 Å are very weak. They suggest that the deep envelope mixing models of Sackmann, Smith, and Despain (1974) may explain these apparent abundance peculiarities in HR 6766, and they further point out that HR 6766 should have a large enhancement of ^{13}C if the deep mixing models are correct.

HR 6766 has one of the smallest CO indices of stars in the CO index survey of HPA and in fact has a much weaker CO absorption than does even a dwarf of similar temperature. As those authors point out, it is not possible to explain the G-band weakness through the depletion of free carbon by CO formation.

In this paper we report a model atmosphere analysis of iron-peak elements, the CNO group, and lithium in HR 6766. Synthetic spectra have been generated to derive the carbon, nitrogen, oxygen, and lithium abundances. Additionally, we have determined the ^{12}C/^{13}C ratio from a curve-of-growth analysis. In § II the observations are discussed, and in §§ III and IV the model atmosphere and abundance analyses are presented. The luminosity and mass of HR 6766 are discussed in § VI. Some preliminary comments on other stars of this class are presented in § V, and we discuss the implications of our work for stellar evolution in § VII.

II. OBSERVATIONS

Both high-resolution spectra and broad-band colors were used in this study. The model atmosphere analysis was based on coudé spectra acquired with the Lick 3.1 m reflector. Dr. W. Bidelman kindly loaned us his 2 Å mm^{-1} spectrum of the region 4000–4700 Å. Two additional spectra at lower dispersion were acquired in each of the following regions: 4100–4700 Å (5.2 Å mm^{-1} dispersion, baked IIa-O plates), 5000–6100 Å (8 Å mm^{-1}, preflashed IIa-D), and 5800–6700 Å (8 Å mm^{-1}, preflashed IIa-F). Broad-band colors taken from the literature were supplemented by 2.3 and 3.6 μm magnitudes obtained with the Wyoming multifilter photometer attached to the 1.5 m telescope of the University of Minnesota–UCSD Mount Lemmon Infrared Observatory; these were used in conjunction with line equivalent widths to determine an effective temperature.

To measure the weak features of ^{12}CN, ^{13}CN, lithium, and [O I] lines, spectral segments 30 Å in length were obtained at 8000, 8055, 6710, 6300, and 6363 Å using the McDonald Observatory coudé echelle spectrometer and a reticon 1024-element silicon diode array (Vogt, Tull, and Kelton 1978). The resolution was 0.12 Å, and the signal-to-noise ratio was about 200. The [O I] lines in HR 6766 were strong enough to be detected on the photographic spectra as well as on the low-noise scans. The measured equivalent widths of the 6300 and 6363 Å lines were, respectively, 33 mÅ and 13 mÅ (reticon spectra), and 34 mÅ and 18 mÅ (photographic spectra). The good agreement between the two sets of numbers is evidence that the equivalent width scale of the photographic spectra is correct.

Reduction of the photographic spectrograms was accomplished on the Lick Observatory microdensitometer. Equivalent widths of unblended lines of neutral and ionized species of the iron-peak elements (Sc, Ti, Cr, and Fe) were measured; equivalent width agreement between individual tracings was typically 10%. The infrared photometry was reduced according to standard procedures (see Gehrz, Hackwell, and Jones 1974). The results are given in Table 1. We note good agreement between our 2.3 μm magnitude (2.31) and that of HPA (2.32).

III. THE MODEL STELLAR ATMOSPHERE

Our first task in the determination of abundances in HR 6766 was the derivation of an appropriate model atmosphere. For the effective temperature, two methods were used. The first involved matching the spectral energy distribution. Our stellar spectra and the discussion of DLO both indicate that HR 6766 is a giant star of roughly normal atomic line strength for its spectral type (carbon excepted). Johnson's (1966) temperature calibration for giants should therefore be applicable to this star.

Table 1 reveals a large discrepancy between the $V - R$ color of Johnson *et al.* (1966) and that of DLO. The probable explanation for this is that the $V - R$ color of Johnson *et al.* (1966) is an average of

TABLE 1

BASIC DATA FOR HR 6766 (=HD 165634)

Parameter	Value
Spectral type	Gp
Right ascension (1900)	18^h01^m7
Declination (1900)	$-28°28'$
l^{II}	2°88
b^{II}	−4°01
Trigonometric parallax	+0″017 ± 0″010
μ_α	+0″026
μ_δ	−0″034
Radial velocity	−4.1 ± 0.5 km s^{-1}
V	4.55,* 4.57†
$U - V$	1.71*
$B - V$	0.96*†
$V - R$	0.66,* 0.76†
$V - I$	1.18,* 1.30†
$V - [2.3]$	2.25,‡ 2.26§
$V - [3.6]$	2.36§

* Johnson *et al.* 1966.

† DLO.

‡ [2.3] from HPA; V from DLO.

§ [2.3], [3.6] from this study; V from DLO.

three observations, $V - R = 0.693$, 0.553, and 0.705, one of which is discrepant. When the value 0.553 is dropped, all the color information from all observers is consistent with a temperature $T_{\text{eff}} = 4790 \pm 20$ K.

Because of the possibility that the temperature scale of Johnson (1966) is in error or is inappropriate for a carbon-weak star such as HR 6766, we have also derived an excitation temperature, using line widths of iron-peak elements. These and the model atmospheres of Carbon and Gingerich (1969) were fed into the line analysis program WIDTH, sister program to ATLAS (Kurucz 1970), which calculated the abundance inferred from each line. The standard test that all weak lines of a given species should yield the same abundance, independent of the line excitation potential, was applied. The Carbon and Gingerich model temperature derived in this manner was 4670 ± 100 K. The same test was applied to the models of Bell *et al.* (1976), in which account is taken of molecular and atomic line blanketing. The result here was $T_{\text{eff}} = 4800$ K. We adopt $T_{\text{eff}} = 4750 \pm 100$ K as the best estimate for HR 6766.

The comparison of lines of neutral and ionized species of a given element was the only method of determining the surface gravity of HR 6766. Demanding the same abundance from each ionization state gave $\log g = 2.0 \pm 0.4$ for both the Carbon and Gingerich (1969) model and the Bell *et al.* (1976) model.

A value for the microturbulent velocity of $v_t = 2.0 \pm 0.5$ km s^{-1} gave good agreement between the abundances derived from weak and moderately strong lines of the same species.

The overall metal abundance derived from these atmosphere parameters indicates a marginally significant metal deficiency $[\text{Fe/H}] = -0.15 \pm 0.25$, where the standard notation $[X] = \log X_{\text{star}} - \log X_{\text{Sun}}$ has been employed. Table 2 summarizes the atmospheric parameters and iron-peak metal abundances. Attention is drawn especially to the good agreement of all the abundance deficiencies from the solar values. It is clear from the above discussion that HR 6766 appears to be in most respects a normal late G or early K giant.

IV. LIGHT-ELEMENT ABUNDANCES IN HR 6766

In this section the CNOLi abundances and the $^{12}C/^{13}C$ ratio in HR 6766 will be discussed.

a) *Carbon*

The formal analysis of the carbon abundance in HR 6766 is based purely on the G band of CH. No high-resolution data exist for the infrared CO bands. The CN red and violet bands, although weakly present in our data, cannot be used for lack of an independent nitrogen estimate. The C I line at 5380 Å is undetectable in our spectra, and the badly blended C_2(0–0) band is only marginally present at best.

A local thermodynamic equilibrium (LTE) spectrum synthesis method was employed for the CH analysis (see Sneden 1973). For the present work we have limited the synthesis wavelength range from 4290 to 4315 Å, where the relatively strong *Q*-branch lines of the $A\,^2\Delta - X\,^2\Pi$ system appear. The CH and atomic line parameters used here have been previously discussed by Lambert and Sneden (1977). The dissociation energy employed, $D_0 = 3.45$ eV, is in good agreement with the recent determination of 3.46 eV by Brzozowski *et al.* (1976). The total line list of atomic and molecular features amounted to some 500 lines; very few solar absorption features were not completely accounted for with this list. A synthesis of the solar CH region using this set of line data, the HSRA model atmosphere (Gingerich *et al.* 1971), and $\log (\text{C/H})_{\text{Sun}} = -3.33$ (Lambert 1978) showed excellent agreement with the observed solar spectrum.

The G band in HR 6766 was then synthesized. Input consisted of the line list described above, an interpolated Bell *et al.* (1976) model with parameters as discussed in § III, and element abundances. All abundances were initially set to $[\text{M/H}] = -0.25$, and the carbon abundance was varied in the different synthesis attempts. Figure 1 shows part of the CH

TABLE 2

MODEL ATMOSPHERE RESULTS

Quantity	Sun	ε Virginis	ε Virginis − Sun	HR 6766	HR 6766 − Sun	HR 6766 − ε Virginis
T_{eff} (K)	5780	5000	...	4750	...	...
log *g*	4.44	2.75	...	2.00	...	...
v_t (km s^{-1})	1.0	2.0	...	2.0	...	...
Ti I (12)	4.40	4.46	+0.06	4.36	−0.04	−0.10
Cr I (4)	5.19	5.14	−0.05	4.94	−0.25	−0.20
Fe I (33)	7.40	7.38	−0.02	7.25	−0.15	−0.13
Cr II (4)	5.84	5.69	−0.15	5.73	−0.11	+0.04
Fe II (6)	7.25	7.23	−0.02	7.04	−0.21	−0.19
Sc II (5)	3.81	3.82	+0.01	3.84	+0.03	+0.02
Y II (4)	2.55	2.55	+0.00	2.31	−0.24	−0.24
Zr II (2)	...	2.70	...	2.18	...	−0.52
La II (2)	2.08	2.21	+0.13	2.14	+0.06	−0.07

NOTE.—The number in parentheses beside each species name is the number of lines used in the abundance derivation. All abundances are log *N*, where $\log N_{\text{H}} \equiv 12.0$.

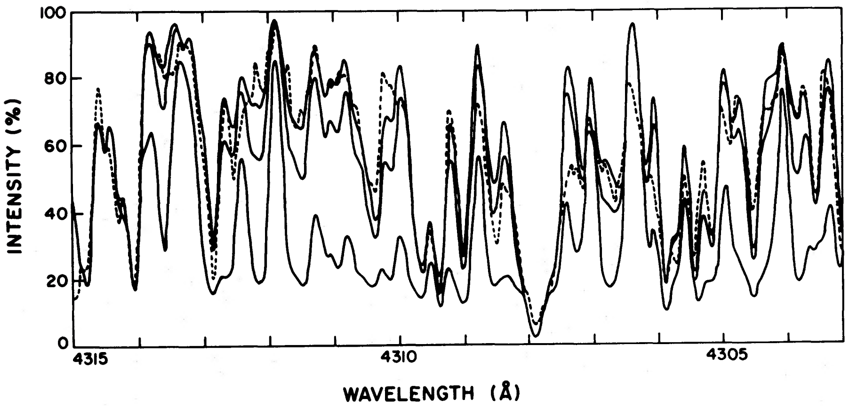

FIG. 1.—A portion of the CH G band in HR 6766. The solid lines represent synthesized spectra with [C/H] = −0.19, −1.19, and −1.49, in order of increasing residual intensity. The dashed line is the observed spectrum.

synthesis, in which the computed spectra are for [C/H] = −0.19, −1.19, and −1.49. It is immediately obvious that carbon is deficient in HR 6766 by a very large factor. Our synthesis indicates an underabundance of carbon a factor of about 17 more than that of the iron-peak elements.

Uncertainties in this result are caused by model atmosphere and CH parameter uncertainties and by the influence of the oxygen abundance in the carbon dissociative equilibrium. Model uncertainties do not appear to be very troublesome. The effective temperature is well determined. Moreover, the gravity determination is somewhat dependent on the assumed temperature. If the model temperature is lowered, for instance, the gravity must also be lowered to keep agreement between neutral and ionized atomic line abundances. The effects on the CH line strengths of changing these two parameters are opposite in sign and of about the same magnitude in this ($T_{\rm eff}$, log g)-domain. Also, since all CH lines are very weak, uncertainties in microturbulence do not affect the CH line strengths. Therefore, model atmosphere uncertainties cannot significantly alter the derived carbon abundance by more than ±0.2 in the log. The CH line parameters are known quite well (see the discussion by Lambert 1978). A conservative uncertainty in the carbon abundance due to the oscillator strength and dissociation energy errors is ±0.1. Finally, if one takes note of the nearly normal oxygen line strengths (see § IV*b*) along with a fairly high temperature and low gravity for HR 6766, it is clear that the assumption of [O/Fe] = 0.0 does not seriously affect the carbon result. Test equilibrium calculations were made with the oxygen varied by a factor of 2. This produced a carbon uncertainty of a little less than ±0.1 in the log. Furthermore, no correction for the $^{12}C/^{13}C$ ratio is necessary, since isotope shifts for the CH lines used here are very small. Considering all the sources of uncertainty, a carbon abundance of [C/H] = −1.49 ± 0.25 is derived. This abundance is consistent with the weakness or absence of other carbon-containing molecules in HR 6766.

b) *Nitrogen*

The CN red and violet systems may both be used to obtain the nitrogen abundance. The CN red ($A\,^2\Pi$–$X\,^2\Sigma^+$) system, for which individual rotational line measurements are available from reticon spectra (Table 3), provide the primary abundance indication. Curves of growth are computed for the CN red system with our adopted stellar model. Line parameters taken from Lambert and Ries (1977) provide good fits to the CN lines in the solar spectrum (see Lambert and Ries 1977). Comparing the theoretical curves to the observed equivalent widths of the CN lines, assuming [C/H] = −1.49, and taking account of the derived ratio $^{12}C/^{13}C = 4.1$ (see § IV*d*), we obtain [N/H] = +0.23 ± 0.4. The larger error here takes account of the dependence of the nitrogen abundance on the carbon abundance determination.

Synthesis of the CN violet ($B\,^2\Sigma^+$–$X\,^2\Sigma^+$) bands near 4200 Å is used to check the above result. We again adopt the values recommended by Lambert (1978) for the oscillator strengths: $f_{0-1} = 0.00240$ and $f_{1-2} = 0.00425$. Atomic contaminating lines are accounted for in the same manner as in the CH synthesis. Portions of the spectrum synthesis, which cover a total wavelength range from 4197 to 4125 Å, are plotted in Figure 2. Derivation of a nitrogen abundance here is much more difficult than derivation of the carbon from the CH synthesis, owing to the lack of CN features sufficiently isolated from atomic contaminants. Figure 2 does show that the nitrogen is about [N/H] = 0.5, in qualitative agreement with the red system result.

c) *Oxygen*

The oxygen abundance is determined from the equivalent widths (measured from reticon spectra) of the [O I] lines at 6300 and 6363 Å. The values of 33 and 13 mÅ, when compared with theoretical oxygen curves of growth, yield abundances [O/H] = −0.40 and −0.37, respectively ([O I] oscillator strengths are taken from Lambert 1978). We adopt [O/H] = −0.38 ± 0.25.

TABLE 3

MEASURES OF RED SYSTEM ^{12}CN AND ^{13}CN(2, 0) BAND LINES

		EQUIVALENT WIDTHS (mÅ)	
λ (Å)	LINE	HR 6766	HR 6791
	^{12}CN Lines		
7992.297.....	P_1 19	...	45
7992.297.....	Q_2 27		
7995.015.....	Q_1 26	14	39
7995.640.....	R_1 35		
7995.640.....	R_2 36	15	38
7995.640.....	P_{12} 15		
8000.261.....	Q_2 28	12	36
8003.213.....	P_2 22	11	23
8003.553.....	R_1 36	9	22
8003.910.....	R_2 37	...	21
8010.084.....	Q_1 28	12	35
8015.668.....	P_1 22	6	19
8017.012.....	Q_2 30	12	31
8018.052.....	Q_1 29	...	43
8051.070.....	P_1 26	...	14
8053.064.....	Q_1 33	15	...
8057.272.....	R_1 42	8	22
8062.558.....	Q_1 34	12	36
	^{13}CN Lines		
7991.111.....	R_1 28	...	10
7991.111.....	P_2 15		
7998.205.....	Q_2 22	5	13
8004.554.....	Q_2 23		
8004.728.....	Q_1 21	9	24
8004.781.....	P_2 17		
8010.458.....	Q_1 22	4	11
8015.166.....	R_1 32	...	5
8016.419.....	Q_1 23	5	12
8048.271.....	Q_2 29	6	17
8048.399.....	P_1 21		
8051.731.....	R_1 37		
8051.731.....	P_2 23	5	13
8051.894.....	R_2 38		
8065.027.....	Q_2 31	3	9

NOTE.—The equivalent widths of the ^{13}CN lines at 7998.21, 8048.27, 8051.73, and 8065.03 Å have been corrected before analysis to allow for blending of weak ^{12}CN lines. Here the measured uncorrected equivalent widths are tabulated.

The small carbon abundance in no way affects the oxygen equilibrium; so that potential source of error may be neglected. The quoted error is due mainly to uncertainties in the model atmosphere for HR 6766.

d) *The* ^{12}C/^{13}C *Ratio*

The carbon isotope ratio is derived from the CN red system lines appearing on the echelle-reticon spectra obtained at McDonald Observatory. Figure 3 shows a small portion of one spectrum of HR 6766 along with one of another weak G-band star, HR 6791; Table 3 gives the line measurements. Figure 4 shows the curves of growth for ^{12}CN and ^{13}CN in HR 6766. The separation of the two curves immediately yields $^{12}C/^{13}C = 4.1 \pm 1.5$. The quoted uncertainty is a measure basically of the uncertainty of the small CN equivalent widths; atmosphere and line parameter errors largely cancel out in the comparison of the curves for these almost identical molecules. A qualitative check on this result is provided by the CN violet system. The ^{13}CN (0–1) band head is clearly present on our spectra at $\lambda \approx 4208.4$ Å, but the surrounding spectral region is too contaminated by atomic features to allow use of this weak feature for a quantitative assessment of the ^{12}C/^{13}C ratio.

e) CNO: *Comparison with* ϵ *Virginis*

The CNO abundances for the Sun, ϵ Vir, and HR 6766 are summarized in Table 4. Epsilon Virginis is a representative giant whose surface abundances (CNO and the ^{12}C/^{13}C ratio) reflect the effect of the predicted convective mixing up of CNO–processed material (see Lambert and Ries 1977). HR 6766 is quite markedly carbon-deficient relative to ϵ Vir. However, the nitrogen abundance is about normal for a convectively mixed giant. Oxygen in HR 6766 is about a factor of 2.5 deficient relative to ϵ Vir; in normal convectively mixed giants (e.g., ϵ Vir) oxygen is predicted to be only slightly decreased. The ^{12}C/^{13}C

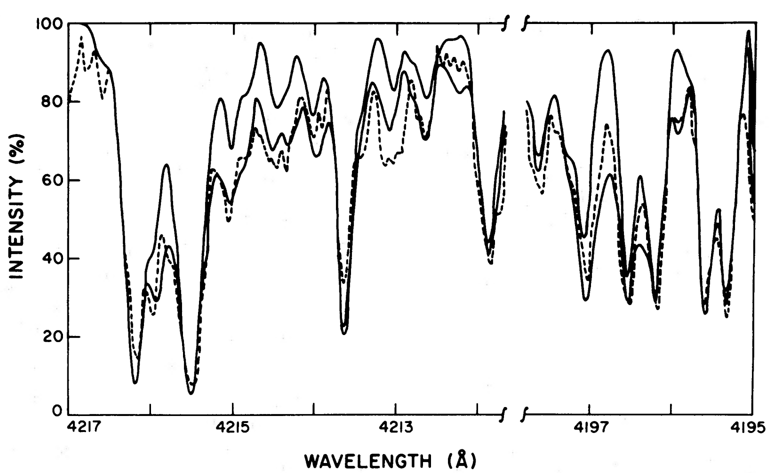

FIG. 2.—The (0–1) and (1–2) band heads of the CN violet system in HR 6766. The solid lines represent synthesized spectra with [N/H] = −0.31 and +0.69. The dashed line is the observed spectrum.

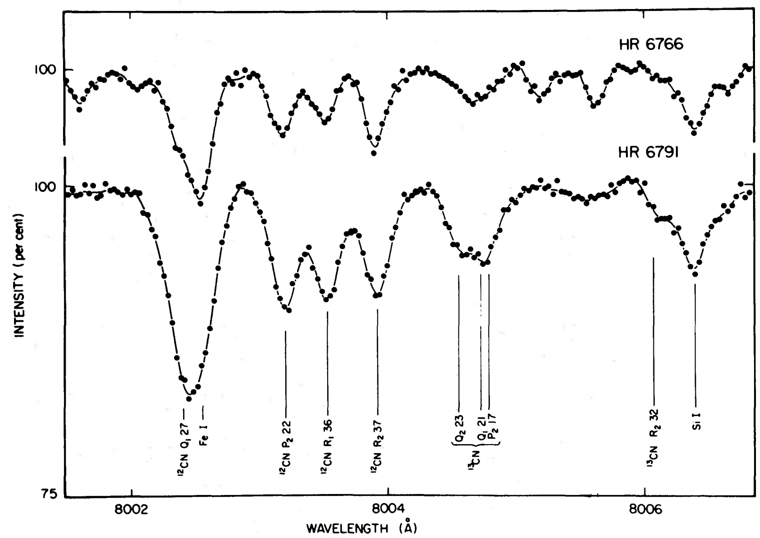

FIG. 3.—The ^{12}CN and ^{13}CN (2–0) band lines between 8002 and 8006 Å in HR 6766 and HR 6791 plotted on an expanded intensity scale. Scans of both stars have been divided by a scan of Vega to remove interfering telluric lines. Residual telluric lines in the spectrum of HR 6766 affect the ^{12}CN R_2(37) line and are responsible for the weak lines at 8005.24 and 8005.67 Å.

ratio in HR 6766 is at the low end of the range observed for G and K giants.

f) *Lithium*

Figure 5 shows a small portion of the reticon spectrum of the region centered on the Li I 6707 Å feature. The wavelengths of major features in the spectrum, which are indicated in the figure, demonstrate that a spectrum synthesis approach is necessary to derive the lithium abundance here. Luck's (1977) line list has been adopted for our synthesis of the feature in HR 6766. The Kurucz and Peytremann (1975) oscillator strength of the Fe I line at 6707.44 Å is too small to reproduce the absorption seen in the solar spectrum (Brault and Müller 1975) or in HR 6766. This oscillator strength has therefore been derived by demanding that the predicted strength of the feature match the observed line in the Sun.

The deepest absorption in the HR 6766 Li I spectrum coincides with the wavelength of the strongest line of the ^{7}Li doublet. Initially, ^{6}Li was ignored in the calculations because of the uncertainty as to whether it actually exists in stellar spectra or whether a V I line is responsible for the extra longward-displaced absorption normally seen in these spectra (Luck 1977). Figure 5*a* shows three synthesis attempts for $\log N(\mathrm{Li}) = +0.60, +0.75$, and $+1.00$. The oscillator strengths for the lithium doublet are well determined (Wiese, Smith, and Glennon 1966). The solar spectrum around the lithium feature was synthesized with the same line list, the HSRA solar model of Gingerich *et al.* (1971), and the recently determined solar lithium abundance (Müller, Peytremann, and de la Reza 1975). The excellent agreement with the observed spectrum (Brault and Müller 1975) that was obtained lends some confidence to the HR 6766 synthesis.

Figures 5*b* and 5*c* demonstrate the difficulty of identifying ^{6}Li in the atmosphere of HR 6766. Luck (1977) has pointed out the existence of a low-excitation-potential line of neutral vanadium which is nearly

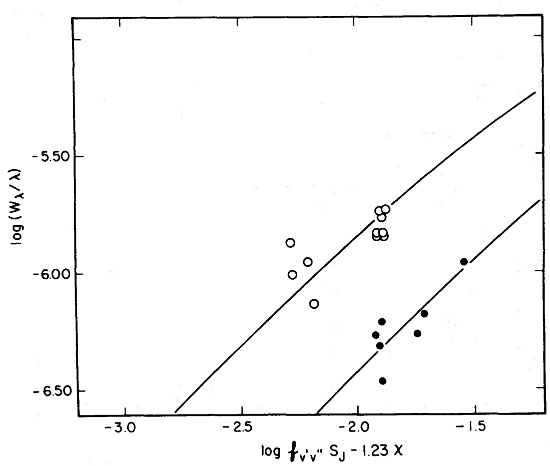

FIG. 4.—Curves of growth for ^{12}CN (*open circles*) and ^{13}CN (*filled circles*) (2–0) band lines in HR 6766. A ^{12}C/^{13}C ratio of 4.1 ± 1.5 is obtained from the horizontal separation between the curves of growth.

TABLE 4

CNO ABUNDANCES FOR THE SUN, ε VIRGINIS, AND HR 6766

Parameter	Sun	ε Virginis	HR 6766
log N(C)....	8.67	8.36	7.18*
log N(N)....	7.99	8.32	8.22
log N(O)....	8.92	8.96	8.54
^{12}C/^{13}C.....	89	20	4.1

* Includes a ^{13}C contribution.

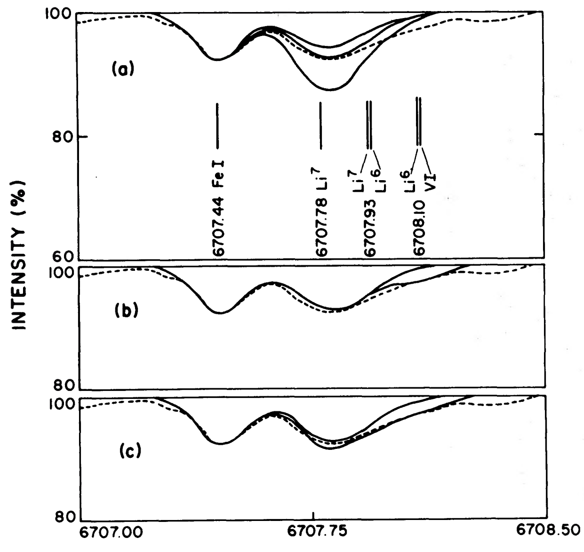

FIG. 5.—The lithium feature in HR 6766. In all cases the dotted curve is the observed spectrum. In (*a*), ^{7}Li and other atomic features have been included in the synthesis attempts. The three solid curves are for assumed lithium abundances log N(Li) = +0.60, +0.75, and +1.00. In (*b*), the same line list has been employed, but with one lithium abundance [log N(Li) = +0.75] and two different V I oscillator strengths (log gf = −2.99 and −2.00). In (*c*), the ^{6}Li doublet has been added to the synthesized spectra. Here, log N(Li) = +0.75, log gf(V I) = −2.23, and lithium ratios ^{6}Li/^{7}Li = 0.0 and 0.25 have been used.

coincident with the wavelength of the stronger member of the ^{6}Li doublet, Kurucz and Peytremann's (1975) semiempirical oscillator strength calculations yield log gf = −2.99 for the V I line. That value was adopted for the "pure ^{7}Li" syntheses shown in Figure 5*a*. In Figure 5*b*, two computed fits to the HR 6766 observations are shown, in which the oscillator strength of the V I feature is allowed to be a free parameter; the synthetic spectra are given with log gf = −2.99 and −2.00. When the uncertainty associated with the oscillator strength of this vanadium line is taken into account, it is clear that almost all of the absorption feature to the red of the ^{7}Li peak may be explained by vanadium alone. We note that one early experimental determination, log gf = −2.33 (Corliss and Bozman 1962), lies between the two oscillator strengths used to generate the Figure 5*b* curves.

In an attempt to see whether the introduction of ^{6}Li into the synthesis would better fit the HR 6766 spectrum, the V I oscillator strength was arbitrarily set to the Corliss and Bozman (1962) value and spectra were computed for various ^{6}Li/^{7}Li ratios. Figure 5*c* shows the spectra calculated for ^{6}Li/^{7}Li = 0 and 0.25. The resulting best fit is not much different from the best fit with only the vanadium line present. We conclude that the presence of ^{6}Li cannot be definitely established in HR 6766. A new experimental determination of the V I gf-value would be of great help in determining the existence of ^{6}Li in this and other stars.

V. COMMENTS ON OTHER CH-POOR STARS

Another weak G-band star, according to Bidelman and MacConnell (1973), is HR 6791. When the very low ^{12}C/^{13}C ratio in HR 6766 became apparent, an effort was made to obtain data for HR 6791. Figure 3 shows part of the CN red system scans for this star. It is apparent that, again, ^{13}C constitutes an appreciable part of the total carbon content. We obtain ^{12}C/^{13}C = 4.5 ± 1.0. This result is, of course, quite insensitive to the assumed effective temperature ($T_{\rm eff}$ = 4500 K). We have also obtained a spectrum covering the Li I doublet; the feature here is much stronger than in HR 6766.

A hotter weak G-band star, HR 885, also appears to have a low ^{12}C/^{13}C ratio; inspection of a high-resolution digicon (Tull, Choisser, and Snow 1975) spectrum of a portion of the CH A–X system shows relatively strong ^{13}CH doublets.

The star 37 Com may also be a member of the class. Yamashita (1967) derived a large (a factor of 7) carbon underabundance through a comparison with two other K giants; this is approximately equivalent to a factor of 14 underabundance relative to the Sun. Yamashita discovered a strong Li I doublet in the spectrum of 37 Com. Tomkin, Luck, and Lambert (1976) obtained the low ratio ^{12}C/^{13}C = 3.4.

While the above abundances appear to place 37 Com in the weak G-band class, this star has one feature that distinguishes it from HR 6766, 6791, and 885: The absorption lines are extremely broad. Broad lines would appear to be the hallmark of the G and K supergiants. The luminosity of 37 Com, log $L/L_\odot$ = 2.68 (Tomkin, Luck, and Lambert 1976), also suggests that it is more like a supergiant than a giant. If 37 Com is a supergiant, this indicates that the weak G-band phenomenon extends to higher luminosities than previously supposed. However a detailed abundance analysis is necessary to confirm the attribution of 37 Com to the class, because Yamashita's carbon abundance analysis appears not to have recognized the extremely broad-lined nature of the spectrum. This feature could be important in analysis of the crowded region containing the CH lines.

VI. THE LUMINOSITY AND MASS OF HR 6766

Several independent luminosity indicators are available for HR 6766. Table 1 lists the trigonometric parallax (Jenkins 1963) as π = +0''.017 ± 0''.010. This value leads to $M_V(\pi)$ = +0.70 (+1.01, −1.92). Clearly, the (small) parallax by itself is insufficient to determine the luminosity of this star. Two spectroscopic indices lead, however, to essentially the same result. First, Wilson (1976) derives a luminosity from the K line M_V(K) = +0.2 ± 0.2. Second, Kemper (1975) derives luminosities of the barium stars from their Hα full widths at half maximum, measured on Lick coudé spectra. The Hα widths appear to be very well correlated with other luminosity determinations for standard stars. For HR 6766, an instrumental profile corrected width has been measured from two 8 Å mm^{-1} spectra tracings. In Kemper's units, $\log H_0 = 1.79 \pm 0.03$, or $M_U(\text{H}\alpha) = 2.2 \pm 0.7$. From Table 1, $U - V = 1.7$, or $M_V(\text{H}\alpha) = +0.5 \pm 0.7$. Mention should be made of effects which could change this value of M_V. Interstellar reddening will make the $U - V$ observed color anomalously large for the temperature class, and the absence of molecular absorption could make $U - V$ anomalously small. HPA estimate the magnitude of first effect as $E(B - V) \approx -0.06$. Also, the observed $U - V$ is about 0.1 mag brighter than the Johnson (1966) color expected for HR 6766. The weakened line absorption effect appears to dominate here, so we adopt $M_V(\text{H}\alpha) = +0.4 \pm 0.7$.

A straight mean of the three absolute magnitude determinations is $M_V = +0.4 \pm 0.6$. Allen (1973) gives the bolometric correction for this temperature of star as B.C. $= -0.44 \pm 0.07$. Then, $M_{\text{bol}} = +0.0 \pm 0.6$ or $\log L/L_\odot = 1.90 \pm 0.24$. Standard relations involving the luminosity, effective temperature, and gravity of a star then give $\log \mathfrak{M}/\mathfrak{M}_\odot = -0.2 \pm 0.7$. The error on the mass is too large for one to say much more than that the mass of HR 6766 is roughly solar. It is possible, however, to rule out a mass larger than about $3\,\mathfrak{M}_\odot$ for this star, which should somewhat constrain its evolutionary interpretation.

VII. DISCUSSION

HR 6766 is likely to be in the helium core burning phase, but a hydrogen shell phase cannot be excluded. Standard stellar evolution calculations predict that red giants in either phase will have undergone a change in surface composition as a result of the convective envelope extending down into a zone which underwent CNO-cycle processing during main-sequence residence. The predicted changes in the CNO abundances and the $^{12}\text{C}/^{13}\text{C}$ ratio are observed in giants of similar luminosity and effective temperature to HR 6766; approximately 75% of the sample analyzed at the McDonald Observatory (Tomkin, Luck, and Lambert 1976; Lambert and Ries 1977) show a surface composition consistent with the predictions. However, other "normal" G and K giants have a $^{12}\text{C}/^{13}\text{C}$ ratio below the predicted range; i.e., surface contamination by CNO–cycled material appears in excess of the predictions. In addition, the strikingly peculiar barium and R (or hot carbon) stars, which also fall in the region of the H-R diagram (Scalo 1976) containing HR 6766, are unexplained by current theories of stellar evolution. The weak G-band stars, therefore, are just one extreme example of stars for which an adequate explanation is unavailable. Detailed information on the surface compositions of these stars should help unravel the mixing and processing events which produce such diverse peculiar stars.

The CNO abundances for HR 6766 suggest a heavy exposure to the CNO cycle, as previously suggested by Norris and Zinn (1977). A characteristic of CNO processing is the rapid establishment of a low $^{12}\text{C}/^{13}\text{C}$ ratio and, at equilibrium, $^{12}\text{C}/^{13}\text{C} \approx 3$. On the reasonable assumption that the $^{12}\text{C}/^{13}\text{C}$ ratio was high in the protostar (i.e., that $^{12}\text{C}/^{13}\text{C} \gtrsim 40$), the observed ratio $^{12}\text{C}/^{13}\text{C} = 4.1 \pm 1.5$ shows that the atmosphere can now contain only a small mixture of material unexposed to the CNO cycle.

A second signature of normal CNO–cycle operation is the conversion of C (and, perhaps, O) into N, with a conservation of CNO nuclei; i.e.,

$$\Sigma(\text{C} + \text{N} + \text{O})_{\text{initial}} = \Sigma(\text{C} + \text{N} + \text{O})_{\text{final}} = \Sigma\,.$$

The observed abundances give $\log \Sigma = 8.72$. Solar abundances (Lambert 1978) give $\log \Sigma = 9.15$. If HR 6766 is slightly metal-deficient ([Fe/H] $= -0.15$, Table 2) and the initial CNO abundances were also deficient (i.e., $[X/\text{Fe}] = 0$ for $X =$ C, N, O), the initial abundances correspond to $\log \Sigma = 9.15 - 0.15 = 9.00$, which is indeed nearly equal, within the errors, to the observed abundance sum of 8.72. The $^{12}\text{C}/^{13}\text{C}$ ratio and the $\log \Sigma$ equally suggest that the CNO cycle has operated on the atmospheric material. Depletion of C with a nearly normal O abundance sets the exposure at between 1 and 100 protons per seed nucleus.

We discuss two different scenarios which might allow the CNO cycle to provide the observed abundances. The normal or deficient *s*-process–element content in HR 6766 (Table 2) probably means that the weak G-band stars are in a different stage of evolution from that of the barium stars, which have similar luminosities. During the convective mixing out which is predicted to affect a giant on the first ascent of the giant branch, the temperature at the base of the convective envelope is too low to allow the CNO cycle to operate. If, however, the temperature were higher, the CNO cycle would process the entire outer convective envelope. The extent of the processing depends on the base temperature and the time scale and duration of the mixing phase. A problem arises in that the high base temperature seems to require a high absolute luminosity; for example, Scalo, Despain, and Ulrich (1975) discuss such hot-bottom convective envelopes around double-shell-source models for which the minimum luminosity is $\log L/L_\odot \approx 4$. A similar luminosity limit applies to the double-shell stars in which mixing and processing arise through thermal pulses. At a luminosity $\log L/L_\odot \approx 2$, these possibilities cannot apply to HR 6766 unless the active phase was followed by a drastic restructuring and drop in the luminosity of the star. However, this luminosity argument should not be given an inordinate weight. The existence of peculiar stars at low luminosities (e.g., weak G-band, barium, and R stars) is evidence that there are missing links in the current ideas on stellar evolution.

The CNO observations do not set severe limits on the conditions in the hot zone. The total exposure must be between 1 and 100 protons per seed nucleus. If the observed N/C ratio is the equilibrum ratio, the base temperature was about $T = 50 \times 10^6$ K. The same ratio can be achieved by a limited exposure at a lower temperature; the equilibrium N/C ratio increases with decreasing temperature. The duration of the processing phase depends on the temperature and density in the hot zone.

The lithium abundance should provide the tightest constraint on the mixing time scales. At the temperatures required for CNO–cycle operation, all primordial lithium is destroyed. Since lithium is observed, its remanufacture is necessary. The probable mechanism (Cameron 1955; Cameron and Fowler 1971) involves the production of ^{7}Be from ^{3}He, i.e., $^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$. If the ^{7}Be remains in the hot zone ($T > 20 \times 10^6$ K), it is destroyed by the reaction $^7\mathrm{Be}(p, \gamma)^8\mathrm{B}$. If the ^{7}Be is convected out to lower temperatures ($T < 3 \times 10^6$ K), lithium can be formed by the electron capture reaction $^7\mathrm{Be}(e^-, \nu)^7\mathrm{Li}$. Since Li production by this mechanism is a sensitive function of the temperature profile and the mixing time scales, the Li abundances should show a marked variation within the class of weak G-band stars. Certainly, additional observations are desirable.

Calculations of the mixing and processing that occur in very luminous stars were reported by Sackmann, Smith, and Despain (1974) and Scalo, Despain, and Ulrich (1975). The observed CNO and Li abundances can be achieved with mixing times of 10^4–10^5 years at the densities considered in the calculations. However, as pointed out above, these specific calculations refer to stellar models with luminosities 100 times in excess of the currently estimated luminosity for HR 6766. Perhaps meridional currents induced in a rapidly rotating main-sequence progenitor provided the mixing down to high temperatures. However, meridional mixing time scales are long and incompatible with the production or preservation of lithium (D. S. P. Dearborn, private communication). Since the lithium abundance is observed to be about normal for a giant, the postulated meridional currents must not involve the surface layers of the star.

The second scenario involving the CNO cycle is built around the evolution of an inhomogeneous main-sequence star which has an outer envelope very deficient in carbon but a normal or enhanced carbon abundance in the interior zone that is processed through the CNO cycle. When the star becomes a red giant, the zone being mixed out will have become nitrogen-rich, and carbon-poor and will possess $^{12}\mathrm{C}/^{13}\mathrm{C} \approx 3$–4. In normal giants, this material is diluted with the unprocessed material in the envelope which is carbon-rich and ^{13}C-poor. However, in an envelope which has virtually no carbon, this dilution is inhibited. The final envelope abundances will depend then on the amount of mixing, but the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio will be approximately that of the inner processed zone. The total carbon abundance will remain low, and nitrogen will be about normal or will increase as the mixing continues. If this sequence of events has occurred, then the observed $^{12}\mathrm{C}/^{13}\mathrm{C} \approx 4$ constrains the envelope to be initially very carbon-poor; since the supposed interior zone has itself become carbon-poor at the red-giant stage, then even a small amount of envelope carbon will cause dilution of interior carbon and hence raise the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio.

This scenario would also happily explain the observed lithium abundance. First, the Li abundance for HR 6766 is consistent with results for giants with normal CNO abundances (see Wallerstein and Conti 1969). Second, the predicted Li depletion resulting from the large convective envelope in a giant is about a factor of 60 (Iben 1966). If the observed Li abundance is corrected, this depletion implies a main-sequence abundance $\log \epsilon(\mathrm{Li}) = 0.75 + 1.78 = 2.5$, which is slightly below the interstellar abundance [$\log \epsilon(\mathrm{Li}) = 3.0$ (Boesgaard 1976)] and consistent with a slight depletion on the main sequence.

The Li abundance serves to exclude severe mass loss as the explanation for the CNO abundances. If approximately 50% of the star is lost during main-sequence evolution, the processed material mixed up in the giant phase is observed without appreciable dilution (Dearborn, Eggleton, and Schramm 1976). The CNO and $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios would resemble those of HR 6766. Since Li in a main-sequence star is confined to about the outer 2% of the star, the severe loss of mass needed to achieve the observed CNO and $^{12}\mathrm{C}/^{13}\mathrm{C}$ abundances would reduce the Li abundance far below the detection limit. This is in conflict with the appearance of a moderately strong Li I line.[1]

Two key difficulties confront this idea of an inhomogeneous main-sequence star: How is a carbon-poor envelope produced? Are inhomogeneous main-sequence stars observed with carbon-poor atmospheres?

Two recent papers have suggested that a separation between gas and grains may occur in the early evolution of a protostar. For obvious reasons, we consider the case of graphite grains. (If separation is effective, silicate grains could also be involved.) Edmunds and Wickramasinghe (1976) argue that graphite grains could be driven out by radiation pressure from the outer parts of massive protostars ($\mathfrak{M} \gtrsim 12\,\mathfrak{M}_\odot$) to leave the envelope deficient in C (and other elements absorbed within and on the surface of the grains). A more detailed analysis is needed to show that such a separation of grains from the gas is possible for the apparently low-mass protostar progenitor of HR 6766. In a study of the dynamical evolution of a globule, Krautschneider (1977) found that the high-mass grains are quickly accelerated toward the center of the cloud. This led to some models of protostars which had enhanced C (for the case of graphite grains) abundances in the core. It is not clear why these schemes for dust-gas separation operate in only a small fraction of stars.

If this second scenario is correct, there must be a small fraction of main-sequence stars in which the atmospheric C abundance is underabundant by at least a factor of 10. In the late F and G stars where the CH G band is strong, it would appear that such stars cannot have escaped detection. However, in the early

[1] The Li is most probably not a spallation product. If spallation is important, the ratio $^{14}\mathrm{N}/^{15}\mathrm{N}$ should be of the order of the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio. A search for $\mathrm{C}^{15}\mathrm{N}$ lines was unsuccessful, and a limit $^{14}\mathrm{N}/^{15}\mathrm{N} > 10$ was set.

F stars where CH is weak or undetectable, carbon-poor stars might await discovery through a search using the permitted C I lines.

Clearly, much more work needs to be done on the weak G-band stars. HR 6766 is not unique (see § VI) with respect to lithium and the low $^{12}C/^{13}C$ ratio. It will be of interest to complete a survey of these stars to see whether Li and ^{13}C are correlated. DLO suggest that the CN strengths may not be tightly correlated with the CH strengths. It is vital to extend the CNO analysis to discover whether CNO–cycle burning is a viable hypothesis in all cases.

HR 6766 is a member of yet one more group of peculiar red-giant stars. The clues provided by its distinctive abundances and those of other types of giants must all be considered in a complete scheme of red-giant evolution.

We thank the directors of Lick Observatory, McDonald Observatory, and Mount Lemmon Infrared Observatory for making telescope time available for this project. Most computations were performed on the University of Wyoming computer, and we acknowledge with thanks a large allotment of computer time. We are grateful to R. Whitaker and L. Cloutman for pointing out the significance of the protostar models to us, and to R. D. Gehrz, J. A. Hackwell, D. A. Briotta, and J. M. Scalo for helpful discussions. Partial support for C. S. was provided by a National Science Foundation grant to R. D. Gehrz and J. A. Hackwell. D. L. L. and J. T. thank the National Science Foundation (grant AST 75-21803) and the Robert A. Welch Foundation of Houston, Texas, for their support.

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